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Ventilation & masks: reducing airborne transmission of COVID-19 in a classroom

Eric A. Schiff

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Summary: We've calculated the number of COVID-19 infections that will be spread from a single COVID-19 "superspreader" to students and teachers in a classroom shared for 4 hours. Without masking and with a low ventilation rate, nearly all susceptible students and teachers will be infected. Neither masking nor ventilation alone is sufficient to reduce the infection rate below 10%. Careful use of surgical masks along with good ventilation reduced the estimated infection rate to 2%. The bar chart below presents the estimated infection rates for low and for good ventilation, and for unmasked, cloth masked, and surgically masked students and teachers. The estimates are based on a comparison with the Guangzhou restaurant cluster of COVID-19 infections, and use the "Wells-Riley" model to calculate infection rates.

KEY FINDINGS

- In a classroom setting with low ventilation and unmasked students, a superspreader's COVID-19 infection will spread to essentially the entire class.
- Neither good ventilation nor good masking, acting alone, reduces the percentage of students infected below 10%
- Used in conjunction, good ventilation and masking reduced the calculated infection percentage to 2%.

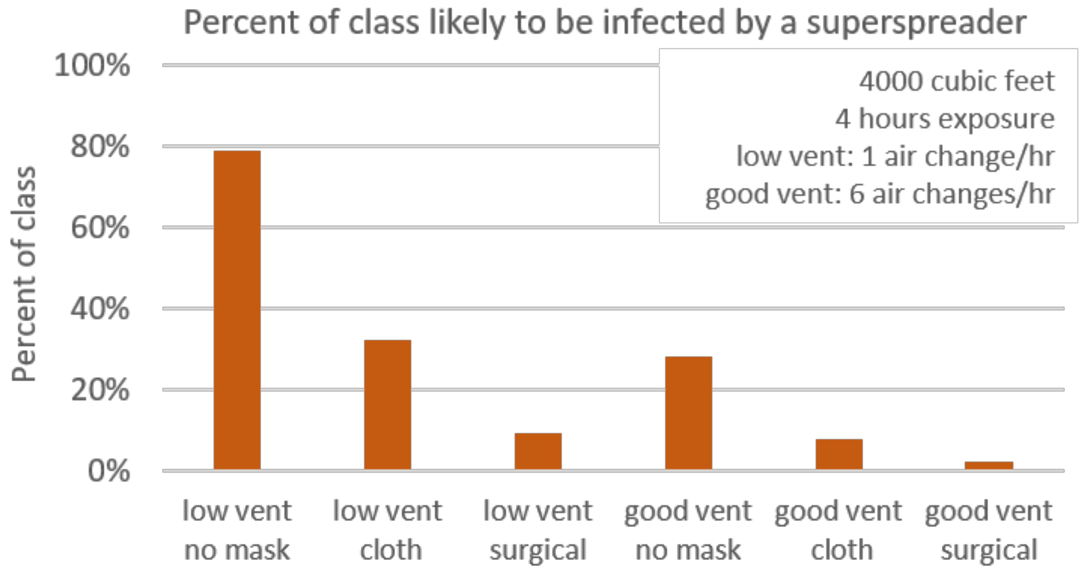

Figure 1: Bar chart showing calculations for the likely percentage of a class that will be infected after 4 hours with a COVID-19 superspreader. Three levels of masking are shown. Low ventilation is one clean air change per hour, which applies in some schools. Good ventilation is 6 air changes per hour.

Virion exposure: In this technical brief we first calculate the exposure of students and teachers in classrooms to SARS-CoV-2 virions following the arrival of an unmasked “superspreader”. We compare this exposure to that of diners in the well-known Guangzhou restaurant cluster of COVID-19 cases.[1] In that event a single person apparently infected about half the diners in a row of tables. The diners overlapped with the infected person for about 1 hour. An air-conditioning unit was operating in their section of the restaurant circulated the air, but it neither purified it nor brought in outside air.

After the arrival of an infected person, and assuming that mixing of the exhaled virions through the room is complete, the COVID-19 virion volume density $c(t)$ rises as:

$$\frac{dc(t)}{dt} = S_0/V - Qc(t)/V\,, \tag{1}$$

where S_0 is the rate (per minute) at which an infected superspreader exhales virions as aerosols, V is the volume of the room (in cubic feet), and Q is the rate (cubic feet per minute or cfm) at which the air in the room is replaced with outside air or the equivalent for filtered recirculated air.[2] We define the *exposure* $e(t)$ of an individual person in the room:

$$e(t) \equiv \int_0^t c(t')dt'\,. \tag{2}$$

The range of rates S_0 for virions exhaled as aerosols by a superspreader is not yet well-established. Exhalation rates as high as 10^5 s^{-1} have been reported.[3] In the following, we chart the *relative* exposure $e(t)/e_G$. e_G is the total exposure for the diners in the Guangzhou restaurant; their exposure was due to a single unmasked and highly infectious individual. Assuming the same rate S_0 for the Guangzhou superspreader and a classroom superspreader, we estimate $e_G = \frac{1}{2}S_0\,(82)^2/3200 = 1.04 \times S_0$ (per cfm).[1] The infectious person was in the Guangzhou restaurant for 82 minutes. The section of the restaurant occupied by the diners who later became ill had a volume of about 3200 cubic feet.

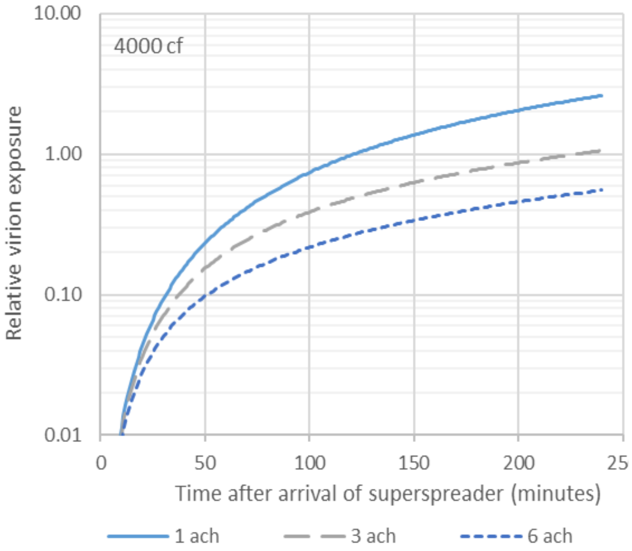

Figure 2: Virion exposure for unmasked students in a classroom following the arrival of a superspreader. Exposure is calculated relative to the exposure of relative to diners in a Guangzhou restaurant event. Results are shown for three ventilation rates (clean air changes per hour (ach)).

Starting with $c(0) = 0$, we solved for the relative exposure $e(t)/e_G$ in a 4000 cubic foot classroom; the superspreader, students, and instructor are all assumed to be unmasked. Results for three different purification/air exchange rates (in air changes per hour) are illustrated in the chart.[4] Note that the vertical axis is logarithmic. As can be seen in the uppermost curve, at 1 air change per hour the exposure of an unmasked individual matches the Guangzhou exposure (82 minutes) after 120 minutes. The longer time to reach the same exposure as in Guangzhou is due mainly to the air change rate of 1 per hour. The air change rate in the Guangzhou restaurant was very low, and we’ve assumed that it was much less than 1 per hour. After 4 hours, the exposure is nearly triple that of the diners in Guangzhou. With 6 air changes per hour, the exposure is about 0.6 that of the Guangzhou diners.

Infection probability: After 240 minutes, we estimate the probability of infection P for the students and instructor class using a version of the Wells-Riley form:[5]

$$p = 1 - \exp(-\,0.60 \times e(240)/(M^2 e_G))\,. \tag{3}$$

We have introduced a masking factor M. We assume that the rate of exhalation of virions by an unmasked superspreader ($M = 1$) is reduced by this factor. We apply the same factor for the reduction at which other individuals inhale virions due to masking. The factor of 0.60 in the exponent was set to match the Guangzhou infection probability $p = 45\%$, where by definition the exposure was e_G and the masking factor was $M = 1$ (unmasked).

Without masking, at 1 air change each hour, $e(240)/e_G = 2.6$, which yields an infection probability of 79% for the students and teacher. With 3 air changes per hour, a four hour exposure is essentially the same as that of the Guangzhou diners, who had a 45% infection rate. With 6 air changes per hour the relative exposure after 4 hours is 0.55, yielding an infection rate of 28%. 6 air changes per hour is at the upper end of typical classroom ventilation.[6] The first conclusion is that, without masking or other risk reduction measures, a superspreader's infection will be widely spread to other occupants even with good interior ventilation of classrooms.

Masking changes these rates substantially. For cloth masks, estimates are that $M \cong 2$; for surgical masks, $M \cong 4$.[2,7] We used these factors to prepare the bar chart in the summary section above. In Fig. 3, we present the calculated dependence of the infection probability after 4 hours for varying ventilation rates for the three masking levels (unmasked, cloth, and surgical). The error bars go back to the proportion $p = 0.45$ of the diners who were infected in the Guangzhou restaurant cluster. For $n = 20$ diners the standard error in p is $\sqrt{p(1-p)/n} = 0.11$ (binomial distribution formula). The error bars on the chart are based on propagating this standard deviation for p through the Wells-Riley formula (equation (3)).

It is evident that superspreader outbreaks of COVID-19 can be mitigated only when air changes, masking, and other measures are integrated in each classroom. A wider summary of these measures was published recently.[2]

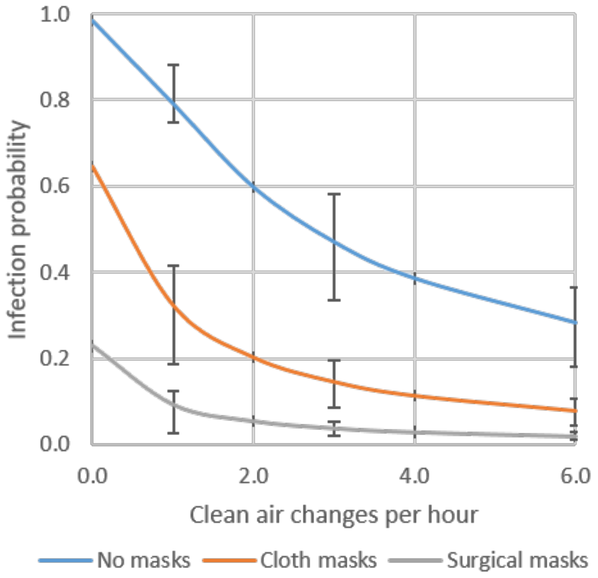

Figure 3: Wells-Riley infection probability for students four hours after the arrival of a superspreader. Calculations are shown without masking, with cloth masks for all persons, and with surgical masks for all persons.

The likelihood that an asymptomatic, infected person is also a superspreader isn't known. It has been argued recently from epidemiological data that the percentage of infected individuals who broadcast SARS-CoV-2 virions so vigorously is statistically insignificant to a population's basic reproduction number R_0.[8] R_0 is the typical number of individuals who catch COVID-19 from an infected individual, and it must drop below 1 for a pandemic to end. Nonetheless, even occasional incidences of widespread infection in a school setting could lead to re-closings, with substantial harm to educational goals in addition to the harm from the infections themselves.

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About the Author

Eric A. Schiff, Ph.D., is interim director of SyracuseCoE (Syracuse Center of Excellence in Environmental and Energy Systems) and Professor in the Department of Physics at Syracuse University. email: easchiff@syr.edu.

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[2] Jensen Zhang, “Integrating IAQ control strategies to reduce the risk of asymptomatic SARS CoV-2 infections in classrooms and open plan offices”, *Science and Technology for the Built Environment* **26**, 1013-1018 (2020), DOI: https://doi.org/10.1080/23744731.2020.1794499. The effective ventilation rate Q is the product of the actual air flow and a factor that allows for imperfect removal or denaturing of virions in recirculated air.

[3] J. Ma, *et al.,* “Exhaled breath is a significant source of SARS-CoV-2 emission”, medRxiv preprint https://doi.org/10.1101/2020.05.31.20115154 .

[4] The air changes per hour (ach) is calculated as $60 \times Q/V$, where the units of Q are cubic feet per minute and V is the room’s volume (in cubic feet).

[5] The original Wells-Riley form assumes a time-independent density of airborne virus; we have generalized the calculation to include the initial increase of the virion density following the arrival of the superspreader in the room. The use of a relative exposure presumes that classroom occupants and the diners in Guangzhou have similar inhalation rates and other factors of disease susceptibility. The Wells-Riley concept of a “quantum” for airborne transmission of disease is commonly assumed in studies of ventilation effects on infections, but other forms have been studied. See G. N. Sze To, C. Y. H. Chao, “Review and comparison between the Wells–Riley and dose-response approaches to risk assessment of infectious respiratory diseases”, *Indoor Air* **20**, 2–16 (2010). https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7202094/#b51 ; doi: https://doi.org/10.1111/j.1600-0668.2009.00621.x

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